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"The diligent farmer plants trees, of which he himself will never see the fruit."
Cicero

Humans have long exploited the climate-altering effects that trees provide through shade from a hot sun and shelter from strong winds (Hall et al., 1958). Behavior that initially produced greater physical comfort evolved into purposeful planting, selection, and tending to increase and expand the multiple benefits trees can provide including food, fiber, fuel, and medicinal products. Agroforestry systems (AFS) integrate woody perennial plants with agricultural crops or animal production on the same land area. A fundamental advantage of AFS is that the combination of trees with understory plants or animals has greater potential for production of food, forage, and fiber than any one element alone. A numerical scale to express this multiple-product concept as a land equivalent ratio was developed for AFS by Keesman et al. (2007). Agroforestry systems have great potential to increase per unit land area productivity as the trees exploit resources (light, water, and nutrients) through their multilayered architecture, deeper rooting, and extended growing seasons that may not be as readily captured by annual crops. The inherent benefits of agroforestry also include enhanced ecosystem services, increased ecological and economic diversity, and the ability to protect or restore vulnerable or degraded soils. These multiple benefits illustrate AFS's great potential to contribute to achieving the Millennium Development Goals to reduce hunger, poverty, disease, and environmental degradation (Garrity, 2004).

Due to innate variation in climate, soil characteristics, and socioeconomic conditions, there is a rich diversity of AFS around the world. Agroforestry systems in the tropics and subtropics are often designed to mimic the highly productive natural forest ecosystems there and may involve multiple species with vertical stratification within the canopy. Much research has been devoted to the cultural and production aspects of tropical and subtropical AFS, producing numerous research articles and several technical books (e.g., Young, 1989; Nair, 1993; Schroth and Sinclair, 2003; Nair et al., 2004; Batish et al., 2008). Agroforestry concepts have been more slowly adapted to temperate regions. As a result, considerably less information is available on temperate AFS (Byington, 1990; Long, 1993; Gordon and Newman, 1997; Garrett et al., 2000). The low adoption of agroforestry practices in temperate regions can be attributed to several factors including concern

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regarding tree–crop competition (especially for nutrients and water in drier climates), readily available and relatively inexpensive external inputs (e.g., fuel, fertilizer, and mechanization) that are often unavailable or too expensive in the tropics, and a cultural reluctance to "farm with trees."

While cropping and forestry components of the different AFS have received considerable attention, soil management aspects have not been developed to a comparable level. Young (1997) and Schroth and Sinclair (2003) are the only books with a focus on soil management aspects of AFS. Many principles of soil management were developed specifically for arable cropping systems on soils formed predominantly under grasslands. Traditionally, forest soil science has been considered a specialty area of soil science due to distinct differences between soils formed in forests or grasslands (Jenny, 1941). Forest soils stand apart due to the influence of the forest vegetation including the forest litter, tree roots, and associated organisms on forest soil processes and properties (Wilde, 1958; Armson, 1977; Pritchett and Fisher, 1987). In forest ecosystems, litterfall on the soil surface is the primary annual organic input and it is the decomposition and mixing of the litter layer by micro- and macrofauna that has profound implications for C and nutrient cycling and the physical characteristics of forest soils (Dickinson and Pugh, 1974; Cadisch and Giller, 1997; Berg and Laskowski, 2006). Soil management in AFS requires an integration of the features and processes of soils with simultaneous crop and tree culture.

The ability of trees to modify the local microclimate creates a special ability for AFS to adapt to climate change (Lin, 2007; Calfapietra et al., 2010). Long-term shifts in temperature and precipitation patterns may result in "normal" conditions that are outside the optimal range for crops currently under cultivation in an area. Another climate-related environmental stress is with regard to the extremes of episodic events. Agroforestry systems are inherently more resilient to climate change and extremes than traditional arable cropping systems in two important ways. First, AFS involve multiple species and perennial vegetation, thereby providing greater plant diversity and less vulnerability to climate stress than is provided by monocropping and annual species. Second, as mentioned previously, the perennial woody vegetation itself serves to modify the local microclimate by influencing sunlight interception and airflow patterns, offering protection for the understory species from extremes in temperature and damaging winds (Stigter, 1988; Brenner, 1996; Cleugh and Hughes, 2002). Deeper rooting perennial vegetation and tighter within-system nutrient cycling also afford greater resilience to drought and the efficiency of nutrient use further enhances the potential utility of AFS to adapt to the uncertainties of climate (Wallace, 1996; Kho, 2008).

Although AFS are inherently productive and resilient to environmental stresses, sharply increasing global demand for food, fuel, and fiber require even greater intensification of production of each of these commodities on a per unit land area basis. Effective soil management of AFS will require skillful and timely application of existing techniques and development of new techniques to optimize and sustain production of all components of the AFS. We will begin our discussion with a brief overview of five broad categories of AFS: (i) riparian forest buffers, (ii) alley cropping, (iii) silvopasture, (iv) field windbreaks or shelterbelts, and (v) forest farming (Fig. 23|1). This will be followed by a discussion of temperate zone AFS that focuses on soil physical properties, nutrient cycling and pH, and soil biology and ecology. Discussion of unique features of subtropical and tropical AFS will follow with a similar treatment of the properties and processes of AFS in these regions. A summary concludes the discussion by reviewing the major points and unifying principles of soil management in AFS.

An Overview of Agroforestry Practices

Natural riparian corridors occur when trees are distributed in a narrow strip along streams, rivers, or lakes. Planted riparian forest buffers are often a restoration of the natural vegetative cover and are designed to filter nutrients and sediment from overland flow before the runoff enters surface water bodies (Peterjohn and Correll, 1984; Lowrance et al., 1984; Snyder et al., 1998) and/or reduce nutrient fluxes through shallow groundwater (Hubbard and Lowrance,

Fig. 23|1. Examples of agroforestry practices. Clockwise from top left, alley cropping, riparian buffer, field windbreak, silvopasture, and forest farming. Photo credits (clockwise from top left): courtesy of The Center for Agroforestry at the University of Missouri, photo by Lynn Betts, USDA Natural Resources Conservation Service, photo by Erwin Cole, USDA Natural Resources Conservation Service, photo by Todd Groh taken from Nowak et al. (2002), and photo by Scott Josiah, Nebraska Forest Service.

1996). As riparian forests are located along hydrologic flow paths, runoff water and shallow groundwater and the nutrients they convey are available for uptake by the trees and understory vegetation (Lowrance et al., 1984). Much focus on the nutrient cycling processes in riparian forests has been on N cycling and particularly nitrate (NO_3) removal from shallow groundwater (Groffman et al., 1996; Hill, 1996). Riparian plantings are often designed with species and their placement optimized to intercept surface runoff, increase infiltration of the runoff, and encourage plant uptake of water from the vadose zone and groundwater. The primary objective is to slow surface water contribution to the stream and filter out eroded sediment and nutrients to improve stream water quality.

Riparian forests are often highly productive due to the readily available and often nutrient-enriched water in the riparian root zone. Due to their position in the landscape, species within natural riparian ecosystems are generally adaptable to the hydrologic extremes of flood and drought with the ability to tolerate temporary submersion or extend roots to extract water from receding aquifers. For this reason, riparian forests may be more resilient than some other ecosystems to climate-induced stress and variability. Decay of the dead wood and grass and leaf litter will return nutrients and C to the soil. This process and the runoff- and sediment-trapping features of riparian corridors can create concern that these areas may become excessively nutrient enriched unless some management that includes nutrient removal (i.e., biomass harvesting) is employed.

Alley cropping (also referred to as hedge rows or agroforestry intercropping) involves widely spaced trees (in rows, in some other geometric pattern, or in a sparse stand

resulting from thinning an existing forest) with the area between the trees (alleyways) used for agricultural (grains, legumes, or forages) or horticultural (shrubs, berries, or vines) crops (Tang et al., 1990). Successful alley cropping requires careful management to assure a balance between competition for and efficient utilization of light, water, and nutrients by the trees and crops (Gillespie et al., 2000; Livesley et al., 2004). Alley cropping systems do allow a high degree of light, water, and nutrient-use manipulation in both space and time (season). For instance, trimming of tree branches increases light penetration to the understory crop while the decomposing prunings provide a slow-release source of nutrients for the crops and a mulch layer to reduce evaporation (Tang et al., 1990; Palm, 1995). Such AFS systems often require intensive management but can be highly efficient, require low external inputs, and can be economically more profitable than conventional systems (Lu, 2006). Alley cropping is a popular AFS for some high-value crops including coffee [*Coffea* L. (Rubiaceae)] and tea [*Camellia sinensis* (L.) Kuntze] and even lower-value row crops or forages.

The architecture and management of silvopasture AFS can be very similar to alley cropping AFS, especially for the tree overstory, but with an understory of forages for consumption by grazing animals instead of growing crops (Sharrow, 1999; Garrett et al., 2004; Schnabel and Ferreira, 2004; Mosquera-Losada and Giguerio, 2005). Silvopastures are a managed analog to natural savanna ecosystems with widely spaced trees and grasses in the open spaces that are often found in a vegetative transition zone between forests and grasslands (Dyksterhuis, 1957). Silvopastures may also represent a transition in land use when trees are planted into existing pasture and grazed for some years until light levels beneath the trees are insufficient for forage growth or when forages are planted beneath a recently thinned forest. Like alley cropping, management of silvopastures requires a balance of resource utilization between trees and forage with the added grazing animal element. Influence of the tree canopy on light penetration, water use, and temperature are key factors affecting forage production and quality and the ability to support grazing animals (Lin et al., 1999; Silva-Pando et al., 2002). Effective management or favorable rainfall and temperature patterns will produce more forage and encourage greater stocking density, which may not be sustainable during subsequent suboptimal growing seasons and has important implications for soil quality.

Field windbreaks or shelterbelts are AFS designed specifically for changing the local microclimate primarily by reducing wind speed in their lee (van Eimern, 1964; Bird et al., 1992; Brandle et al., 2004). Shelterbelt plantings consisting of single to multiple rows of trees and/or shrubs have been frequently employed in semiarid areas with extensive plantings in the steppes of Russia (Vyssotsky, 1935) and during the 1930s Dust Bowl in the American Great Plains (U.S. Forest Service, 1935; Droze, 1977). The tree rows reduce wind speed to a distance downwind of approximately 20 times the tree height with multiple beneficial effects on the local microclimate. In general, crop growth in the lee of a shelterbelt is increased due to less evaporation, more plant-available water, and less mechanical stress (Plate, 1971; Rosenberg, 1979; Kort, 1988; Brenner, 1996; Cleugh and Hughes, 2002; Peri and Bloomberg, 2002). Shelterbelts have also been shown to significantly reduce wind erosion (Gupta et al., 1983). Other benefits include trapping snow, increasing wildlife habitat, and improving aesthetics (Cook and Cable, 1995).

Forest farming refers to the cultivation of usually higher-value specialty crops beneath a tree canopy. Forest farming is often used for the cultivation of shade tolerant ornamentals (flowers, ferns, bushes, and decorative florals), medicinals and botanicals (herbs, teas, and natural health products), or food products (mushrooms, fruits, berries, and nuts). A type of forest farming more common in the tropics is the home garden where plants for food products are grown in the understory next to a dwelling. Smith (1953) and Sholto Douglas and de J. Hart (1978) are two classic references for forest farming, both written from a strong ecological perspective for sustainable food production. These writers focused primarily on management of the forest canopy as a food source: fruits and nuts for humans and fodder for livestock. More recently, greater attention has been focused on management of understory species (e.g., ginseng, *Panax* spp.) with the

overstory species now having the primary role of providing a managed microclimate (Hill and Buck, 2000; Rao et al., 2004).

Soil Management in Temperate Agroforestry Practices

Although the next three sections will deal with soil physical properties, nutrient cycling and pH, and soil biology and ecology individually they are, in fact, intimately linked. This linkage is perhaps most easily and directly observed with regard to the recycling of organic matter in the soil and the effect of decomposition pathways on nutrient cycling and the amount and quality of soil organic carbon (SOC). As AFS integrate multiple plant species and soil management practices, this discussion will by necessity include concepts covered in far greater detail in other chapters of this volume. Relevant fundamental principles will therefore not be repeated here, where instead the aim is to briefly introduce and synthesize concepts and then relate the principles, processes, and practices of soil management to AFS.

Soil Physical Properties

The size, shape, and arrangement of soil particles and the gathering of these particles into aggregates have profound effects on the transport of water and energy (heat) in soils. Equally important are the voids among the aggregates through which the dynamic transport processes of two vital fluids, air and water, occur. The form and strength of soil structure is very much influenced by shrinking–swelling processes due to wetting–drying and freezing–thawing cycles (Horn and Smucker, 2005) and biological processes associated with root growth and secretions and the activities of micro- and macrofauna (Angers and Caron, 1998). The amount, size, and connectedness of pores between and within the structural aggregates have a tremendous impact on plant growth as it is through these pores that water (and the nutrients it contains) is absorbed by roots. Well-structured soils are also best able to balance the drainage of excess water and retention of water for plant uptake with the maintenance of a sufficiently oxygenated void space (Gliński and Stępniewski, 1985; Kirkham, 2005). Processes that contribute to good soil structure often lead to increasing SOC content, which has a strong correlation with the amount of plant-available water a soil is capable of storing (Hudson, 1994). Due to the marked difference between the thermal properties of air and water, soil thermal properties are directly correlated with soil water content. Heat and water transport are therefore intimately coupled (Parlange et al., 1998) with important implications for all chemical reactions and biological activity in soils.

Many AFS offer great potential to improve soil structure due to their diversity of plant species and their contrasting growth habits across spatial and temporal scales. Agroforestry systems have produced significantly lower soil bulk density within a multispecies riparian buffer in Iowa (Bharati et al., 2002), beneath a two-row red-cedar (*Juniperus virginiana* L.)–Scotch pine (*Pinus sylvestris* L.) field windbreak in Nebraska (Sauer et al., 2007), and in alley cropping and silvopasture systems in Missouri (Seobi et al., 2005; Kumar et al., 2010). Udawatta and Anderson (2008) reported 2.6 times greater macropores in soil beneath the oak (*Quercus* spp.)–grass agroforestry plantings as compared with the cropped field for the same site as Seobi et al. (2005). The changes in soil pore structure in the AFS at this site associated with differences in bulk density including greater porosity, order-of-magnitude higher saturated hydraulic conductivity, and increased potential water storage were observed already 6 yr after establishment (Seobi et al., 2005; Udawatta et al., 2006). Increased soil aggregate stability beneath a similar *Quercus* spp.–grass AFS in Missouri (Udawatta et al., 2008) also suggests that these changes in soil structure and porosity associated with the AFS are resilient. Although Karki et al. (2009) found a lower percentage of water-stable aggregates in a silvopasture in Georgia, soil penetration resistance was lower in the silvopasture compared with an open pasture.

Infiltration beneath silver maple (*Acer saccharinum* L.) in a multispecies riparian buffer in Iowa was significantly greater than adjacent grass, crop, and pasture sites and was attributed to greater sand content,

macropores from decayed roots, and soil faunal activity (Bharati et al., 2002). Sharrow (2007) however, found 13% higher bulk density and 7% lower total porosity in a Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco)–subterranean clover (*Trifolium subterraneum* L.)–tall fescue (*Festuca arundinacea* Schreb.) silvopasture in Oregon as compared with adjacent ungrazed forest. The silvopasture soil also had a 38% lower infiltration rate but had the same amount of available water at field capacity in the top 6 cm. Cessation of grazing for 2 yr reduced the differences between silvopasture and forest soils with little detrimental effect on forage or tree production. Anderson et al. (2009) reported no significant differences in ponded infiltration between agroforestry buffer strip and no-till row crop areas in an alley cropped watershed in Missouri. Greater water depletion during the growing season was observed in the buffer strip soil that enabled increased recharge during storm events resulting in more water storage and less surface runoff.

AFS effects on soil physical properties and the soil moisture regime are important factors influencing their performance and management. Jose et al. (2000a) and Reynolds et al. (2006) evaluated the tree–crop competition for water in alley cropping systems in Indiana and Ontario and determined that management strategies needed to address tree water use and shading if losses in crop productivity were to be avoided. In contrast, Balandier et al. (2008) found that even though 10 yr-old wild cherry (*Prunus avium* L.) in a silvopastoral AFS in central France had a different rooting pattern than the mixed grass and legume forage, the wild cherry experienced severe competition for water. Carlson et al. (1994) also reported tree water stress for a Douglas fir–subterranean clover–tall fescue silvopasture in Oregon. These results in more water-limited climates contrast with the findings of Gyenge et al. (2008) who found that the deeper roots of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) were able to extract underutilized deep-water reserves in a silvopasture in Patagonia. Clearly, understanding of the relevant processes of soil water storage and plant water use and careful management practices are necessary to avoid adverse impacts on both crop and tree growth and productivity in AFS.

Nutrient Cycling and Soil pH

The observed effects of AFS on soil structure and porosity and the associated changes in the soil water regime have important implications for the biological processes associated with nutrient and organic matter cycling. Litterfall is the primary annual organic input to soils in forests as compared with crop and grassland ecosystems where the primary organic input is from root decomposition (Anderson, 1987; Gale and Cambardella, 2000; Berg and Laskowski, 2006; Kong and Six, 2010). The biochemical makeup of these organic materials (e.g., lignin content and C to N ratio) and their mode and rate of decomposition directly affect the recycling of nutrients and nutrient losses as gaseous emissions or via surface runoff and groundwater flow. Forest ecosystems are generally considered to be more conservative in nutrient cycling with large total nutrient pools but low amounts of available or mobile nutrients located on the forest floor and in shallow soil layers. Forest soils are typified by a thin, organic-rich O horizon over an A and deeper horizons with lower nutrient concentrations due to significant losses of soluble organic N, P, and S compounds and the cations Ca, Mg, and K through leaching (Anderson, 1987). The more extensive tree roots are capable of extracting nutrients from deeper soil layers and nutrient uptake patterns of some species can acidify the soil, thereby accelerating weathering of minerals and furthering nutrient release (Arnold, 1992; Binkley and Giardina, 1998). By contrast, arable soils are typically much more intensively managed with frequent (often annual for N) external nutrient additions, rapid organic matter decomposition, and seasonally large but highly transient pools of plant-available nutrients.

Nair (1993) lists several soil fertility-related benefits that trees can provide in AFS including N fixation, access to deeper sources of nutrients, enhancement of dry and wet atmospheric deposition of nutrients, and release of root exudates, all of which can contribute to increased nutrient use efficiency. Differences in the amounts, properties, and decomposition of tree-, crop-, and animal-derived (silvopasture) organic inputs, while resulting in a more complex system of

nutrient cycling, also create a more diverse and resilient system with potential for synergism as well as competition. Wedderburn and Carter (1999) compared the decomposition of litter from four functional tree types (deciduous N-fixer, evergreen N-fixer, deciduous, and evergreen) for silvopastoral AFS and found initial lignin content and lignin to N ratio controlled the rate of litter decay. They concluded that litter properties could be independent of tree functional group but chemical differences between species were more important than seasonal changes in litter quantity or quality. Forage legumes and animal manures have also been evaluated, especially for supplying N, in silvopasture AFS. Blazier et al. (2008) reported that subterranean clover integrated into a loblolly pine (*Pinus taeda* L.)–Bahia grass (*Paspalum notatum* Flüggé) silvopasture in Louisiana helped retain more P from applied fertilizer or poultry litter in the surface soil layer and resulted in enhanced pine growth. A 10 Mg litter ha^{-1} rate of litter application did result in P accumulation in the surface soil and likely increased N and P leaching potential. Karki et al. (2009) also found benefits of integrating a legume into a silvopasture AFS in Georgia. Crimson clover (*Trifolium incarnatum* L. 'Dixie') overseeded into Bahia grass under longleaf pine (*Pinus palustris* Mill.) resulted in improved forage productivity and forage and soil quality during the hay production period of pasture to silvopasture conversion.

Jose et al. (2000b) found faster release of both N and P from fine roots as compared with leaves from black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) in an alley cropping AFS in Indiana. Plant competition for fertilizer N was considered minimal, however, as N uptake by the black walnut and corn (*Zea mays* L.) crop were not synchronized. Competition for N mineralized from leaf and root tissues could occur but would depend on soil N status and water content. Significant changes in available nutrients, exchangeable acidity, and pH were observed in the surface soil layer beneath a red-cedar–Scotch pine field windbreak in Nebraska 35 yr after the trees were planted (Sauer et al., 2007). Available Ca and Mg were significantly greater and P lower beneath the trees compared with the adjacent cropped fields. Eastern red-cedar (*Juniperus virginiana* L.) leaves are known to contain high concentrations of Ca (Read and Walker, 1950) so the increase in Ca is likely due to Ca uptake by the trees followed by litterfall and decomposition with nutrient incorporation into the surface soil. The comparatively lower P concentration beneath the trees is likely due to P increases in the cultivated field that received several manure applications. Soil pH in water varied from 4.3 to 7.3 and was highly correlated with tree species with the low pH values (and exchangeable acidity and cation exchange capacity) observed near the Scotch pine trees. Soil acidification with various pine species has been observed previously (Coile, 1933; Arnold, 1992; Sariyildiz et al., 2005) while eastern red-cedar has been found to increase soil pH (Coile, 1933; Read and Walker, 1950). It is clear that different tree species can have profound, localized effects on soil chemical properties and nutrient cycling and distribution in AFS.

Forest riparian buffers have often been designed and planted for the principal purpose of extracting nutrients, especially N in the form of NO_3, and P, from overland flow and shallow groundwater. Peterjohn and Correll (1984) reported significant removal of both N and P in surface and subsurface flows across a riparian forest in Maryland. Entry and Emmingham (1996) measured nutrients stored in the litter and surface mineral soil in forest and grass buffers in Oregon and found substantially greater amounts of macronutrients (P, K, Ca, Mg, and Fe) and Mn in the surface litter and soil of the forest but smaller quantities of the Zn, B, and Cu. Continuous nutrient accumulation in both litter and soil could saturate the storage capacity, requiring biomass removal (tree harvest) to promote greater uptake and continued removal of nutrients transported from agricultural fields. Poplar (*Populus* ×*euroamericana* 'Eugenei') trees within a multispecies riparian buffer in Iowa immobilized significant N (37 kg ha^{-1} yr^{-1}), thereby slowing or preventing N losses to water resources or the atmosphere (Tufekcioglu et al., 2003). This substantial quantity of N could be removed from the system via tree harvest or could re-enter the terrestrial nutrient cycle following death of the tree and decomposition of the woody biomass.

Soil Biology and Ecology

Studies of soil biological processes face numerous challenges including aspects of soil heterogeneity, the large diversity of organisms, and the abundance of interacting processes occurring in the dynamic soil environment (Andrén et al., 2008). Soil biological processes are especially important in AFS as biotic systems respond to the physical environment (temperature and moisture regimes) created by the tree–crop canopies and they often control the rate and direction of C and nutrient transformations. Studies of biological aspects of forest litter decomposition abound (e.g., Andersson et al., 2004; Berg and Laskowski, 2006; Kanerva and Smolander, 2007; Niemi et al., 2007) including potential impacts of climate change (Cotrufo et al., 1994; Arp et al., 1997; Oren et al., 2001; Busse et al., 2009). Many of the principles relating to C and nutrient cycling discovered for forest ecosystems have direct application to AFS. Recent attention on C cycling in AFS has focused on global climate change and the C sequestration potential of the different systems as affected by local climate and soil properties (Nair, 1993; Schroeder, 1994; Kort and Turnock, 1999; Nair and Nair, 2003; Schoeneberger, 2008). Two other areas of intense interest concern the use of soil enzyme activity as an indicator of soil quality and the role of mycorrhiza in enhancing nutrient use efficiency and water uptake (Haselwandter and Bowen, 1996; Ingleby et al., 2007; Trasar-Cepeda et al., 2008).

Udawatta et al. (2008 2009) reported that enzyme activities (fluorescein diacetate hydrolase, β-glucosidase, dehydrogenase, and glucosaminidase) increased in the tree rows of a pin oak (*Quercus palustris* Münchh.) alley cropping AFS in Missouri. The tree strips also had increased soil C and N as compared with the adjacent corn–soybean [*Glycine max* (L.) Merr.] fields. Mungai et al. (2005) studied soil enzyme activities and microbial functional diversity in a pecan [*Carya illinoinensis* (Wangenh.) K. Koch]–bluegrass (*Poa trivialis* L.) and a silver maple–corn–soybean alley cropping AFS in Missouri and found differing results for the two sites. They concluded that functionally different microbial populations may occur under the pecan trees that may affect nutrient availability in the cropped alleys. Ingleby et al. (2007) reported that trees and crops can share the same arbuscular mycorrhizal fungi (AMF) but it may take years for the colonization to benefit the growth of the crops. Lacombe et al. (2009) also reported contrasting results of microbial diversity and stability for two alley cropping sites in Quebec and Ontario and recommended that further research was needed to assess the role of tree roots in maintaining AMF and other beneficial organisms.

Szajdak et al. (2002) analyzed soils beneath a mixed species shelterbelt in eastern Poland to discern the influence of the shelterbelt on N transformations and the chemical structure of the humic acids in the soil organic matter. They reported that with increasing distance into the shelterbelt inorganic and organic N decreased as did the chemical maturity of the humic acids and the amino acids bound to them. Ivannikova et al. (2008) also found significant variation of soil properties, including biological activity, with distance and depth beneath a >100-yr-old shelterbelt in southeastern Russian. Data from different locations within the local microtopography (depressions and elevations of 10–30 cm) exhibited distinct patterns of biological activity as measured by CO_2 evolution during soil incubations. Sauer et al. (2007) reported significantly greater SOC in the surface 15 cm of soil beneath a 35-yr-old shelterbelt in Nebraska as compared with the adjacent cropped fields (Fig. 23|2). The observed increase in SOC represents an annual accrual of 10.6 g m^{-2} yr^{-1} and stable C isotope analysis indicates that fine particulate organic matter (POM) accounted for 21% of the SOC beneath the trees and 79% of the fine POM was tree-derived (Hernandez-Ramirez et al., 2011). Haile et al. (2008; 2010) also used stable C isotope signatures to determine that the majority of SOC in deeper soil layers down to 1.25 m were derived from tree sources in four slash pine (*Pinus elliottii* Engelm.)–Bahia grass silvopastoral sites representing Spodosols and Ultisols in Florida. Minimizing site disturbance and the increased diversity of plant species in AFS have been credited with reducing C losses and increasing the stability of SOC stocks.

Subtropical and Tropical Agroforestry Practices

General Differences from Temperate AFS

Similar to AFS in temperate regions, subtropical and tropical AFS can make substantial contributions to enhancing soil quality. Several significant differences in AFS structure and functioning can be noted across biomes as biophysical conditions among these biomes also differ. Solar radiation input is typically abundant, vertically incoming, and well distributed throughout the year in the tropics and subtropics compared with temperate regions. This basic difference entails the need to optimize spatial arrangements of plant canopies in multistrata configuration in subtropical and tropical AFS to maximize radiation capture, and hence maximum net ecosystem productivity (Budowski, 1993; Nygren et al., 1993; Mafongoya et al., 2006). Several subtropical and tropical crops [e.g., coffee, cacao (*Theobroma cacao* L.), ginger (*Zingiber officinale* Roscoe), black pepper (*Piper nigrum* L.), pearl millet [*Pennisetum glaucum* (L.) R. Br.], and vanilla (*Vanilla planifolia* Andrews) are also typically grown in association with shading trees (e.g., *Erythrina* spp., *Inga* spp., *Cordia alliodora* Ruiz & Pav., *Acacia mangium* Willd., *Azadirachta indica* A Juss.) as they effectively tolerate shading and need protection from both excessive solar radiation and associated fluctuations in environmental conditions (e.g., temperature) to express their optimum yield potential (Muschler et al., 1993; Nygren et al., 1993; Kapp and Beer, 1995; Budowski and Russo, 1997; Beer et al., 1998; Nair et al., 1999; Somarriba et al., 2001). An example of the beneficial microclimate modification by tree overstories within subtropical and tropical AFS was documented in the Western Sahel by Payne et al. (1998). They observed soil temperature reductions up to 6°C at 5-cm depth and important enhancements in crop yield for pearl millet, corn, and sorghum [*Sorghum bicolor* (L.) Moench] when plants were grown under acacia trees [*Faidherbia albida* (Delile.) A. Chev.]. Crop growth failed with no tree shading under these extreme Sahel conditions.

Since the degree of shade tolerance differs across crops or forages and local environmental conditions vary too, the optimum AFS canopy structure seems to be unique for every case. Cusack and Montagnini (2004) studied the gradual transition from degraded pastureland to silvopastoral systems in Central America and concluded that intermediate tree canopy openness resulted in maximum regeneration and growth. Soto-Pinto et al. (2000) indicated

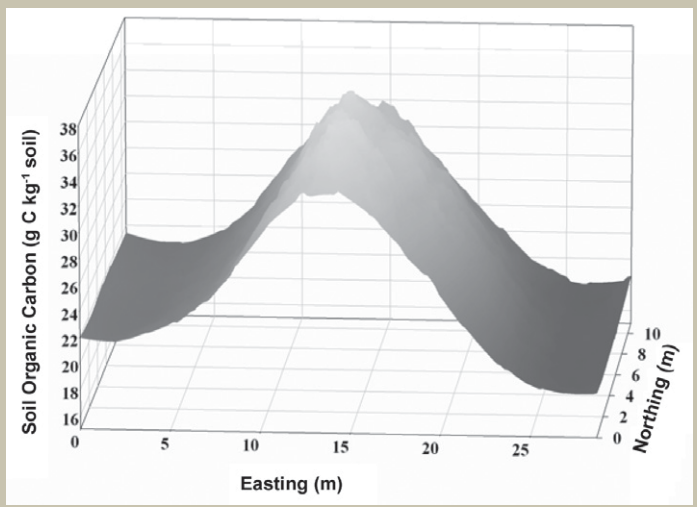

Fig. 23|2. Spatial distribution of soil organic carbon (SOC) storage from a sampling grid beneath and adjacent to a two-row shelterbelt in eastern Nebraska (Sauer et al., 2007). The uncultivated tree zone was from 5.5 to 23 m with the tree rows centered at approximately 11 and 14.5 m.

that maximum yield in coffee (a plant with C3 photosynthetic pathway) occurred with 38 to 48% of shade cover (measured by photographic techniques) in southern Mexico (Fig. 23|3). Conversely, sparse tree canopies seem more desirable for growing C4 crops. Rao et al. (1998) presented yield data for corn grown with and with no trees suggesting a direct association between light availability and productivity of the crop component in AFS (Fig. 23|4). Earlier data by Salazar and Palm (1987) also supports decreasing yield in certain crops with proximity to the tree rows and as a result of excessive shading.

Another biophysical difference across biomes impacting AFS structures and functioning is the typically low soil fertility in tropics and subtropics relative to soils in temperate regions (Tiessen et al., 1994; Sanchez et al., 1997). Low-fertility acid soils cover 41, 27, and 26% of tropical America, Africa, and Asia, respectively (Sanchez, 1976; Mafongoya et al., 2006). Tropical acid soils partly depend on nutrient recycling from deep soil layers to maintain fertility in the surface soil, thus nutrient uptake by deep tree roots in tropical and subtropical AFS can contribute to this process (Szott et al., 1999; Chikowo et al., 2003; Mafongoya et al., 2006). This nutrient capture and recycling by tree components in AFS is completed through nutrient incorporation into biomass production, deposition on soil surface through litterfall, and decomposition (Rao et al., 1998; Nair et al., 1999). This organic matter cycling is basic for sustaining soil productivity particularly in tropical environments (Ohu et al., 1994; Mafongoya et al., 2006). In addition, soil organic matter turnover is generally much faster in subtropical and tropical AFS due to higher temperatures as observed by Oelbermann et al. (2004a, 2006a, 2006b) when comparing alley cropping systems in Costa Rica and southern Canada. They also suggested the need of increasing organic matter inputs in tropical AFS to support stable pools of both soil organic matter and associated nutrients. These multiple reports collectively indicate both much more dynamic and more growth-limiting nutrient levels in subtropical and tropical AFS than in temperate regions.

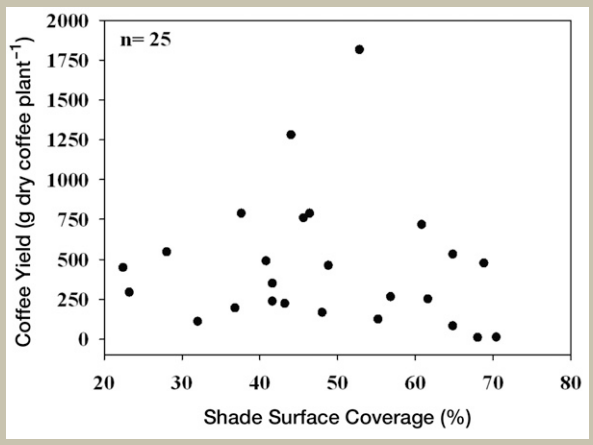

Fig. 23|3. Shading effects on coffee yields when maintaining a constant coffee population density (2200 plant ha^{-1}). Adapted from Soto-Pinto et al. (2000).

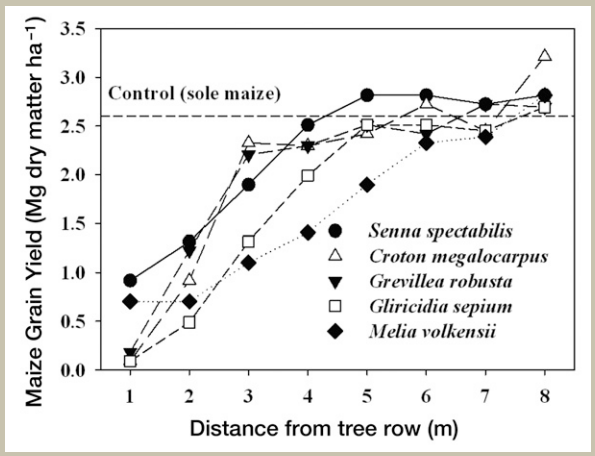

Fig. 23|4. Corn yield in alley cropping systems as a response to presence of trees (2 yr after establishment) and distance from tree rows for five different tree species at Machakos, Kenya. Adapted from Rao et al. (1998).

Types of AFS and Practices in the Subtropics and Tropics

The ample diversity of AFS in subtropics and tropics has been documented by Nair (1985), Lal

(1991), Montagnini (1992), Budowski (1993), and Brenner (1996). Although all AFS are tree-based systems, multiple differences in spatiotemporal arrangements, number of components, and level of interactions can be noted in subtropical and tropical AFS inventories. Practices range from simple AFS such as living fences of *Erythrina* spp. (Budowski, 1987; Russo, 1990a; Budowski and Russo, 1993) to much more complex AFS such as silvopastoral systems (Russo, 1990b; Montagnini, 1992; Montagnini et al., 2003) with high level of spatiotemporal interactions. Agroforestry technologies such as fodder banks are not considered AFS due to the absence of any direct interaction among system components (Nair, 1985); however, they are frequently mentioned in classification studies of agroforestry practices as they can provide similar products and services (animal food, fuelwood, timber, fiber, etc.). Typical examples of AFS and agroforestry practices in subtropics and tropics with potentially beneficial impacts on soil management are alley cropping, rotation or shifting, browsing or grazing, taungya, and orchards or home gardens.

Alley cropping is a simultaneous, spatially zoned system in which crops (typically annual crops) or pasture (mainly for mechanized forage harvest) are cultivated in wide alleys between single or multiple rows of trees or bushes as discussed above. These AFS in the tropics and subtropics typically involve a tree legume with the purpose of supplying N-rich mulch (Lal, 1991). With some exceptions, this N contribution to the overall system has consistently resulted in enhanced crop productivity. Okogun et al. (2000) found increased corn yield as a response to alley cropping with *Albizia lebbeck* (L.) Benth, *Gliricidia sepium* (Jacq.) Kunth, or *Leucaena leucocephala* Lam. de Wit. Similarly, several earlier studies suggested increasing crop productivity for alley cropping systems such as *L. leucocephala, Inga edulis* Mart., or *Erythrina poeppigiana* (Walp.) O.F. Cook with corn, and *Acioa barteri* (Hook. f. ex Oliv.) Engl. with cassava (*Manihot esculenta* Crantz) (Siaw et al., 1991). Collectively, these results support enhanced N availability status in alley cropping systems, particularly under low natural soil fertility conditions. An additional benefit can be obtained when alley cropping systems with *L. leucocephala* hedgerows are established in steep tropical lands resulting in the formation of terraces (Lal, 1991) leading to more intensive land use capacity than on natural slopes. A typical management practice in alley cropping systems is pruning of the trees or bushes to facilitate crop growth as well as a way to enhance nutrient recycling.

One of the most traditional forms of AFS is shifting cultivation that consists of annual crop species—e.g., rice (*Oryza sativa* L.), corn, beans (*Phaseolus vulgaris* L.)—for 1 to 3 yr followed by natural regeneration of trees and woody species for 5 to 40 yr. This sequential system has been traditionally implemented by small farmers by applying slash-and-burn practices that sharply increase the dynamics and release of nutrients (Rao et al., 1998). This practice increases soil organic matter mineralization and nitrification rates during the first few years of cultivation (Montagnini and Buschbacher, 1989). Jordan (1992) showed a sharp increase in cation (Ca, Mg, and K) and NO_3 availability after cutting and burning of Amazon forest in Venezuela; however, pronounced nutrient depletions can occur after 2 to 3 yr as reported by Jordan (1992) and Tiessen et al. (1994). Leaching, runoff, and nutrient removal in harvests can account for a large portion of these nutrient losses caused by shifting cultivation. As pointed out by Sanchez (1976), shifting cultivation was traditionally viable only based on availability of sufficient land area; however, the increasing pressure for land use has restricted land availability, and hence, it has shortened (or completely eliminated) the fallow time between cropping periods, thereby impeding the restoration of natural soil conditions. Therefore, enhanced shifting cultivation systems such as improved fallows (3–4 yr) in sequence with annual crops have been proposed (Sanchez et al., 1997; Nair et al., 1999). These enhanced shifting cultivation systems substitute regeneration of natural vegetation by planting of selected tree species (typically legumes) during the fallow period (Mafongoya et al., 2006) and replace the practice of burning by mulching (Rao et al., 1998). As suggested by Rao et al. (1998), although nutrient availability can be limited shortly after mulching relative to burning, mulching assures higher soil organic matter contents, long-term steady nutrient release, reduced nutrient losses, and enhanced soil biological activity.

As a land management system and as a result of its unique spatial-temporal arrangement, taungya systems may be considered another alternative AFS for traditional shifting cultivation. With origins in Southeast Asia, taungya can be described as the planting of annual crops in the early stages of a forest plantation (Gajaseni, 1992). A typical example is teak (*Tectona grandis* L. f.) plantations in Thailand or Myanmar with annual crops—e.g., dryland rice, corn, pineapple [*Ananas comosus* (L.) Merr.], pepper, peanuts (*Arachis hypogaea* L.), cassava, and soybeans—cultivated between tree rows within 2 to 3 yr after tree planting. Since small farmers are involved in crop cultivation and in tree culture, this system can reduce the destruction of natural forest typically caused by traditional shifting cultivation. In the long term, however, sustainability of taungya systems has been questioned. Bruijnzeel (1992) reported a wide nutrient imbalance (i.e., P, Ca, K, Mg) in taungya experiments with *Pinus caribaea* Morelet and *Gmelina arborea* Roxb. in eastern Amazonia Brazil, and conifers *Agathis dammara* (Lamb.) Rich. in Indonesia and *T. grandis* in the Western Plains of Venezuela. This assessment estimated elevated nutrient losses (i.e., P, Ca, K, Mg) caused by timber extraction ranging from 33 to 82% across nutrients, locations, and types of sequential rotations. Leaching and soil erosion would further enlarge this nutrient deficit under repeated taungya systems. Bruijnzeel (1992) indicates the need for supplementary fertilization to the trees to sustain productivity after two successive forest rotations in low-fertility tropical soils.

Multiple-purpose trees intentionally grown in pasture with the primary purpose of animal browsing and/or grazing is also an extensively practiced AFS in the subtropics and tropics. Additional critical attributes of these silvopastoral systems are the appropriate compatibility of tree species with the grass component as well as the ability of the tree component to supply shelter to grazing animals (Ibrahim and Camargo, 2001). Successful examples of native tree species growing in silvopastoral systems of Costa Rica are *Alnus acuminata* Kunth (Russo, 1990a), *Hieronyma alchorneoides* Allemão and *Dipteryx panamensis* (Pittier) Record & Mell (Montagnini and Sancho-Mora, 1990; Montagnini et al., 2003), and *Cordia alliodora* (Ruis &. Pav.) Oken (Camargo et al., 2000). Since this type of AFS compresses more components (i.e., grass–tree–animal) and unique processes such as animal manure production take place, the level of interactions in silvopastoral systems is typically much higher (Montagnini, 1992). This increased level of interactions is expected to contribute additional resilience to the overall system (Sanchez, 1999) compared with pasture in monoculture.

Soil Physical Properties

Implementation of AFS in the subtropics and tropics can effectively enhance numerous soil properties. Data by Nyamadzawo et al. (2007) suggests enhanced soil structure and increasing infiltration rates in years following improved fallows compared with both natural fallow and continuous corn in tropical Africa. They also indicated that if improved fallows are followed by corn cultivation with no-tillage management, these enhancements in soil structure and infiltration persist over 2 yr during the post-fallow period. Reports by Hulugalle and Kang (1990) and Torquebiau and Kwesiga (1996) support significant reductions in soil bulk density and penetration resistance and increases in infiltration in response to alley cropping with *G. sepium* and improved fallow with *Sesbania sesban* L. Merr., respectively. Data by Hulugalle and Kang (1990) and Hulugalle and Ndi (1993) also support overall improved soil physical properties from alley cropping related to amelioration of surface seal formation following intensive rainfall events. After examining several cropping systems and soils, Dalland et al. (1993), Mapa and Gunasena (1995), and Buresh and Tian (1998) consistently associated enhancements in soil bulk density and infiltration with concomitant increases in soil aggregate stability and organic matter accumulation. Reports by Schroth et al. (1996), Torquebiau and Kwesiga (1996), Schroth (1999), and Schroth and Zech (1995) collectively suggest increases in soil organic matter, root growth and turnover, litterfall, and macrofauna activity as leading to enhanced soil physical conditions under AFS. Van Noordwijk et al. (1991) established the key role of tree roots in enhancing soil pore connectivity. Macropore formation by tree roots and associated increases in macrofauna activity can be an

effective contribution of the tree component to enhance soil physical properties in AFS.

Land use systems involving multistrata canopy and mulching are also expected to show reductions in raindrop impact and runoff water (amount and velocity) as well as enhanced rainwater redistribution (Wallace, 1996). Reductions in ambient temperatures by tree shading in AFS can decrease both soil water evaporation and surface desiccation (Lal, 1991; Rao et al., 1998), typically leading to a more uniform soil water availability in semiarid subtropical and tropical regions. Collectively, these multiple favorable effects of AFS on soil physical properties also have major implications for minimizing soil losses by wind and/or water erosion. As documented by Lal (1991), Mapa and Gunasena (1995), Alegre and Rao (1996), and Mafongoya et al. (2006), AFS typically diminish soil erosion risks compared with crop-based farming systems. Soil erosion may also be decreased in AFS by combining tree species with different growth habits that rapidly create a dense, uniform ground coverage in early stages of the system (Juo et al., 1995; Buresh and Tian, 1998).

Nutrient Cycling and Soil pH

A beneficial contribution of the tree component in AFS in the tropics and subtropics to nutrient cycling and productivity is the increase in N supply via biological fixation of atmospheric N_2. Biological N_2 fixation is typically followed by incorporation of N into tree biomass (shoots + roots) and the subsequent recycling via soil organic matter decomposition (Haggar et al., 1993; Nair et al., 1999). As reviewed by Giller and Wilson (1991), numerous studies indicated the high potential of N-fixing trees (including legumes and several nonlegumes) in supplying additional N to other components in AFS in tropical and subtropical regions. Improved fallows based on tree legumes can accrue up to 200 kg N ha^{-1} in tropical soils (Giller et al., 1997). Similarly, Dalland et al. (1993) documented enhanced N supply to corn due to alley cropping particularly with *L. leucocephala* in tropical Africa. However, literature also indicates that although large amounts of N can be fixed in subtropical and tropical AFS, most of this N does not become readily available in the short term (Buresh and Tian, 1998; Mafongoya et al., 1998). Data by Oelbermann et al. (2004a, 2004b, 2006b) in Central America suggest low N mineralization rates in alley cropping systems that may restrict the success of the overall AFS. Mafongoya et al. (1998) indicate only up to one-fifth of recent N additions via tree pruning, leaf drop, or litter may be readily released and taken up within the next crop growing season. Although N losses due to leaching and gaseous emissions cannot be neglected (Chikowo et al., 2004), the remaining 80% of the total N added via fixation and biomass cycling can be categorized as slow-release N. This relatively low N availability to plants can occur due to soil microbial N immobilization in early stages of the mineralization process and the recalcitrant N characteristics in the biomass of some tree legumes (Haggar et al., 1993; Palm, 1995). After examining biomass characteristics in tropical tree legumes, Buresh and Tian (1998) and Mafongoya et al. (1998) suggested adopting the ratio of lignin + polyphenol to N in tree foliage as an indicator of N mineralization rates in recently added litter in AFS as narrow lignin + polyphenol to N ratios strongly correlated with increasing N mineralization rates. In addition to understanding biomass attributes that precondition N release, the extent to which low N mineralization rates can limit AFS productivity also depends on the synchrony between N availability and crop N demand (Palm, 1995; Mugendi et al., 1999). There is a critical need for additional mechanistic understanding regarding soil N availability and its management in AFS.

An additional benefit to soil fertility of tree components in AFS is the nutrient uptake by deep-rooting trees from subsoil layers where nutrients are not accessible to most annual crops, and the subsequent nutrient redistribution to the topsoil via biomass production and decomposition (van Noordwijk et al., 1996; Nair et al., 1999; Buresh et al., 2004). The effective retrieval of deep soil NO_3 by trees in AFS and the resulting enhancement in overall N efficiency are well supported by multiple reports (Birch, 1964; Hartemink et al., 1996; Shepherd et al., 1996; Mekonnen et al., 1997; Jama et al., 1998b; Chikowo et al., 2003; see also Fig. 23|5). This NO_3 capturing effect by deep-rooted tree species may potentially also mitigate NO_3 leaching (Birch, 1964; Shepherd et al., 1996) and associated groundwater contamination. In addition to these reports about enhancement in N supply to

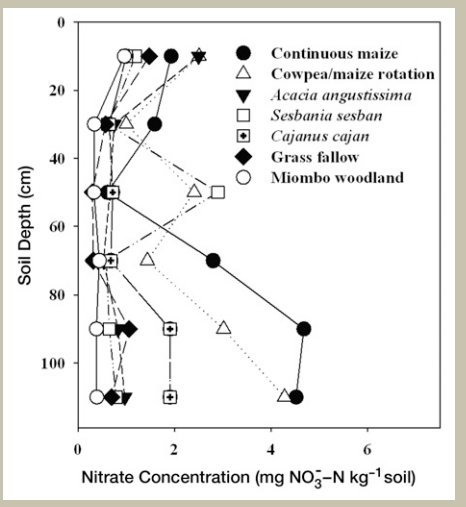

Fig. 23|5. Soil NO_3 profiles for corn grown in diverse cropping systems in eastern Africa. Adapted from Chikowo et al. (2003).

crops in AFS, favorable retrieval and cycling effects by deep tree roots have been also observed for mobile basic cations. Dalland et al. (1993) reported increasing soil Mg and K content in response to mulching in alley cropping with *L. leucocephala*. Similarly, Sanchez (1999) indicated enhanced K status in corn cultivation after a *S. sesban* fallow. These results collectively suggest that utilization of soil nutrients (and water) in AFS is greater than in monocultures as AFS typically combine shallow-rooted species with deep-rooted species. However, as pointed out by Lal (1991), very low-fertility acid soils may have insufficient nutrients available in deep soil layers to be recycled by tree roots. In addition, van Noordwijk et al. (1996) suggested shallow roots of trees in AFS may compete for nutrients and water (particularly under limiting soil moisture) with the crop and/or pasture components of AFS perhaps limiting uptake by crop roots. Understanding and managing competition for nutrients and water constitutes a key feature for sustainability and success in AFS, in particular for simultaneous AFS such as alley cropping (Sanchez, 1995; Rao et al., 1998).

Soil Al toxicity coupled with low P availability constitutes a fundamental biophysical constraint for crop productivity in the subtropics and tropics (Sanchez et al., 1997). The potential role of tree components in AFS for both Al toxicity alleviation and increasing P availability remains unclear as existing reports are inconsistent across geographic locations and AFS types. Buresh and Tian (1998) and Nair et al. (1999) indicated that AFS typically cycle insufficient P to sustain the overall system productivity. Similarly, Lal (1991) suggested that since AFS typically enhance soil N availability, nutrients such as P and Zn may become growth limiting. Conversely, although total P remained unaffected, data by Maroko et al. (1999) revealed that both natural and improved fallows in tropical soils can effectively increase preferential P allocation into labile fractions of soil organic matter. Soil P availability would be enhanced under these conditions assuming that these labile organic matter fractions can act as a source of readily available forms of P (Rao et al., 1998). Both Rao et al. (1998) and Mafongoya et al. (2006) suggested that abundant production of Al-binding organic acids by trees in AFS may result in soil Al detoxification and the associated enhancement in soil P availability. Although not clearly understood, reports by Pande and Tarafdar (2004) and Satter et al. (2006) indicated that mycorrhizal infections in tree roots can potentially contribute to enhanced soil P availability in AFS.

Strategic use of fertilizers has been proposed to alleviate pronounced nutrient deficiencies in tropical and subtropical AFS. Reports by Muschler et al. (1993), Szott and Kass (1993), Jama et al. (1998a), and Khanna (1998) across a variety of ecophysical conditions and management systems suggest the need for rational use of P fertilizers in AFS. Selection of tree species to be included in AFS can also critically impact nutrient management plans as different tree species may comparatively have both different nutrient requirements and diverse effects on soil fertility (Juo et al., 1995; Buresh and Tian, 1998; Rao et al., 1998; Montagnini et al., 2003; Mafongoya et al., 2006).

Soil Biology and Ecology

Biological activity is essential for maintaining soil fertility (i.e., nutrient turnover and availability) in sustainable cropping systems (Sanginga et al., 1992; Buresh and Tian, 1998; Rao et al., 1998; Mafongoya et al., 2006). These studies also suggest the lack of a comprehensive understanding of soil biological processes in tropical and

subtropical environments. However, they also indicated that critical soil biological attributes such as macrofauna activity can be considerably enhanced by establishing AFS. Buresh and Tian (1998) found two to three times greater earthworm populations with different improved fallows than with continuous corn cultivation in western Africa. Budowski and Russo (1997) also indicated a greater earthworm population if *Erythrina* spp. is grown as shading trees in croplands in Central America. Likewise, Rao et al. (1998) presented data for macrofaunal biomass indicating five times more macrofaunal biomass with improved fallow as compared with corn monoculture. In their study, earthworm biomass was 10 times higher in the improved fallow. Sileshi and Mafongoya (2006) also found increasing numbers of several macrofaunal litter transformers as a response to AFS establishment. Similarly, Adejuyigbe et al. (1999) reported two- to six-fold higher soil microarthropod population densities (i.e., *Acari, Collembola*) in soil under fallows (i.e., planted and natural) compared with continuous cropping (i.e., corn and cassava) in southwestern Nigeria. They associated these enhancements in macrofaunal counts with both increasing lignin contents in tree litterfall resulting in relatively slower litter decomposition as well as greater soil water content. Collectively, these results support the contribution of the tree component in AFS to preserve and potentially enhance agricultural soils by restoring macrofaunal population and activity. As an additional ecosystem service, AFS such as living fences and silvopastures can also increase opportunities for biodiversity conservation through improved interconnectivity (i.e., biological corridors for wildlife) among surrounding natural ecosystems (León and Harvey, 2006).

Underlying mechanisms for improving soil biological and ecological processes in AFS may include increasing soil organic matter and microclimate modifications, particularly via shading. Favorable conditions for biological activity in AFS are directly promoted by: minimal soil disruption, mixture of plant species for enhanced biodiversity, permanent vegetative ground cover (with rapid regrowth), and litter management. Increased biomass input would typically lead to increased soil organic matter in AFS. In addition, microclimate modifications in AFS (i.e., via tree shading that buffers extreme temperature fluctuations) can also reduce soil organic matter decomposition rates. Many studies support these trends across a wide variety of ecosystems and AFS. Compared with continuous corn cultivation, data by Nyamadzawo et al. (2008) shows 28% greater C retention (to 20-cm depth) after 2 yr following their improved fallow management in eastern Africa. Rao et al. (1998) reported higher C accretion rates as a function of increasing plant residue inputs in coppicing improved fallow systems. After comparing numerous AFS in southern Mexico, Roncal-García et al. (2008) found increasing C accumulation to be associated with greater biodiversity and degree of complexity (i.e., number of tree species and morphology). Mapa and Gunasena (1995) in Sri Lanka and Oelbermann et al. (2006b) in Central America also reported higher C accumulation in response to alley cropping implementation.

Summary

Knowledge integrated in this chapter about the impacts of AFS on soil management in temperate, subtropical, and tropical biomes support the beneficial, holistic role of tree components in agricultural land use systems. Compared with annual monocultures, AFS can enhance several soil physical properties, improving soil resilience and reducing soil erosion losses. Likewise, in AFS, soil fertility and nutrient use efficiency of companion crops can be improved by trees through the release of nutrients from leaf, root, and woody components as well as via biological N_2 fixation and cycling (if N-fixing trees are included), and uptake and recycling of various nutrients from deep subsoil horizons. Contribution of AFS to biological diversity and activity, typically through sheltering effects coupled with both increases in amounts of SOC and enhancement of food web dynamics, can also be substantial. These various prospective advantages may reflect underlying mechanisms in the functioning of AFS oriented to optimize the utilization of resources (e.g., light, water, nutrients) in both time and space. Current research should increase the focus on identifying the best spatiotemporal combinations of system components (e.g., trees, crops, pastures, animals) to make AFS functioning and structure more

efficient, with the aims of attaining optimum productivity and profitability with maximum environmental services and reduced economic risks. When assessing AFS performance as a whole, careful balance between crop productivity goals and benefits from the tree component needs to take into account potentially hidden beneficial, long-term contributions of trees to the overall system.

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